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# Each Blade a Single Crystal

*Clever casting techniques produce jet engines that can withstand 2,000-degree temperatures, allowing unprecedented efficiency.*

Lee S. Langston

The very first flight powered by a jet engine took place in Germany on August 27, 1939.

Now most of the 19,400 airplanes in the global air-transportation fleet are jets, with about 5 million passengers boarding them every day. On heavily traveled North Atlantic routes between North America and Europe, there are about 800 flights daily; it is possible for a passenger to reach almost any part of the planet within a day. Yet the jet engine remains largely unsung as both a masterpiece of energy conversion and a means of modern transit.

Since it was invented, the aviation version of the gas turbine (a common workhorse for the generation of electricity) has been continuously upgraded by legions of engineers. Following the laws of thermodynamics, one of the most fruitful paths toward better performance has been finding ways to increase thermal efficiency—the amount of fuel that actually turns into the desired output and not waste heat—by raising the temperature at which the jet engine operates.

Creating turbine parts that can survive extreme heat has been a major engineering challenge. Meeting it has required fundamentally rethinking the material structure of the turbine blades, making metals do things that they do not normally do in nature. The result has been a largely invisible revolution,

but one that is responsible for much of the ongoing success of the jet age.

## Superalloys Beat the Heat

All turbines operate on similar principles: A gas or other fluid turns a rotor, which can do useful work. In a jet engine, air is taken in and compressed, then fuel is added and combusted to heat the air, which then turns the rotor blades of a turbine. The hot exhaust is then expelled through a nozzle to create thrust. (See “The Adaptable Gas Turbine,” *Technologue*, July–August 2013.)

Gas turbine thermal efficiency increases with greater temperatures of gas flow exiting the combustor and entering the turbine. In modern, high-performance jet engines, the temperature of this gas can exceed 1,650 degrees Celsius (non-aviation gas turbines operate at 1,500 degrees or lower, whereas military jet engines can reach 2,000 degrees, which exceeds the boiling point of molten silver). Since the 1950s, in high temperature regions of the turbine, special blades and vanes are made from a combination of metals based on high-melting-point nickel. This material is called a “superalloy” because it retains strength and resists oxidation at extreme temperatures.

The nickel in this superalloy has a crystal structure called a *face-centered cubic*, meaning it’s a cube with an atom at each corner and one at the center of each side. Other metallic elements are alloyed with nickel to produce a microstructure with two variant types, or *phases*, of crystals, one of which contains different elements at specific locations in the cubic crystal. When this phase is equally distributed in the larger nickel alloy, it helps stabilize the microstructure at elevated temperatures, resulting in high strength and corrosion resistance.

Such superalloys, when they are cast using conventional methods in a vacuum furnace to prevent oxidation, soften and melt at temperatures between 1,250 and 1,400 degrees. This temperature limit means blades and vanes closest to the engine combustor may be operating in gas path temperatures far exceeding their melting point, and thus must be cooled to typically eight- to nine-tenths of the melting temperature to maintain integrity.

To maintain these temperatures, turbine airfoils subjected to the hottest gas flows must be cast with intricate internal passages and surface hole patterns needed to channel and direct cooling air (bled from the compressor) within and over their exterior surfaces. After casting, the working surface can be sprayed with ceramic thermal barrier coatings to increase life and act as a thermal insulator (allowing inlet temperatures a few hundred degrees higher).

To create blades that can endure these extreme conditions, engineers began digging deeper into the structure of the blades themselves starting in the 1960s. Conventionally cast turbine airfoils are polycrystalline, consisting of a three-dimensional mosaic of small metallic crystals, or *grains*, formed during solidification in the casting mold. Each grain has a different orientation of its crystal lattice from its neighbors’. The interfaces between these crystals are most often not aligned along the crystals’ axes, resulting in what are called *grain boundaries*.

Untoward events happen at grain boundaries, such as increased chemical activity, slippage under stress loading, and the formation of voids. Among other problems, these conditions can lead to *creep*, an insidious life limiter: the tendency of blade material to deform at a temperature-dependent rate under

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stresses well below the yield strength of the material. Corrosion and cracks also start at grain boundaries. Thus grain boundaries greatly shorten turbine vane and blade life, and require lowered turbine temperatures with a concurrent decrease in engine performance.

One can try to gain sufficient understanding of grain boundary phenomena so as to control them. But in the early 1960s, researchers at jet engine manufacturer Pratt & Whitney Aircraft (now called simply Pratt & Whitney, and owned by United Technologies Corporation) set out to deal with the problem by eliminating grain boundaries from turbine airfoils altogether. Its researchers invented techniques to cast single-crystal turbine blades and vanes, and designed alloys to be used exclusively in single-crystal form.

### All Going the Same Direction

As part of that effort, mechanical engineer Maurice (Bud) Shank left the faculty of the Massachusetts Institute of Technology to form the Advanced Materials Research and Development Laboratory (AMRDL) in North Haven (then later in Middletown), Connecticut, for Pratt & Whitney. Over its subsequent 10-year life, AMRDL pioneered single-crystal superalloy technology. AMRDL was an excellent example of industry using fundamental and applied research to create and bring to market a superior product within a decade. At its peak the staff numbered more than 200 scientists, engineers, and technicians, conducting research and development on all aspects of single-crystal technology, from casting, alloy development, coatings, joining, and repair.

I developed a picture of AMRDL's early days from discussions with Maury Gell and Tony Giamei, both retired Pratt & Whitney researchers and managers. As they tell it, one of Shank's first acts was to hire Frank VerSnyder from jet engine manufacturer General Electric. VerSnyder had developed a concept that was a step toward single crystals, because it eliminated grain boundaries in blades in what's called the *spanwise* direction, from root to tip, during casting. (General Electric did not realize the potential of VerSnyder's concept, so had been reluctant to exploit or patent it.)

VerSnyder's first invention and patent for Pratt & Whitney, developed in 1966, was a turbine blade that contained only columnar grains, which form along the length of the blades. He accom-



These turbine blades have had their surfaces etched with acid to reveal their inner structure. The pair at left are single crystals, whereas the pair in the middle are directionally solidified, with all the crystal boundaries going in one direction. The pair at right are made up of small crystal grains, with numerous boundaries. Blades of single crystal have significantly increased life spans under extreme temperature conditions. (Image courtesy of Alcoa Howmet.)

plished this formation with a process called *directional solidification*, which is carried out in a vacuum chamber furnace, and involves pouring molten superalloy metal into a vertically mounted, ceramic mold heated to metal melt temperatures, and filling it from root to tip. The bottom of the mold is formed by a water-cooled copper chill plate, with a knurled surface exposed to the molten metal. The chilled knurls cause crystals to form from the liquid superalloy, and the solid interface advances.

A temperature-controlled enclosure surrounds the mold, and maintains a temperature distribution on the outside surfaces of the mold so that the latent heat of solidification is removed by conducting it through the solidified superalloy to the chill plate. As the solidification front advances from root to tip, the mold is slowly lowered out of the temperature-controlled enclosure. After molding, these blades are then cleaned and machined to be mounted in an engine.

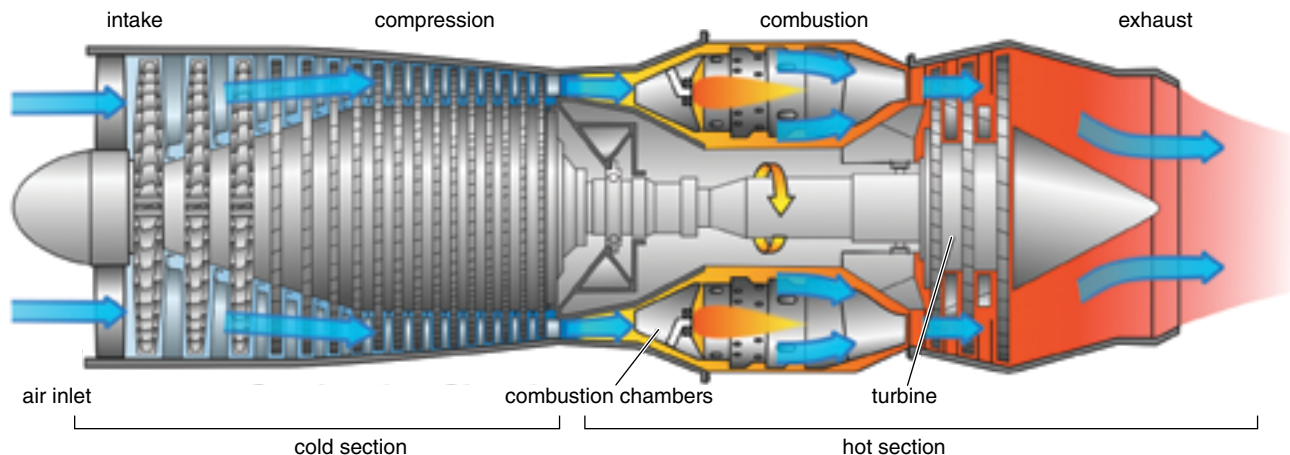
The final result is a turbine airfoil composed of columnar crystals or grains running in a spanwise direction. In the case of a rotating turbine blade, where spanwise centrifugal forces along the blade are characterized by accelerations on the order of 20,000 times the force of gravity, the columnar grains are thus now aligned along the major stress axis. Their alignment strengthens the blade

and effectively eliminates destructive crack initiation between grains in directions normal to blade span. In gas turbine operation, directionally solidified turbine blades have much improved ductility and thermal fatigue life. They also provide a greater tolerance to localized strains (such as at blade roots), and have allowed small increases in turbine temperature and performance.

Once material properties were measured and manufacturing technique perfected, directionally solidified turbine blades and vanes were ready for engine application. Their first use by Pratt & Whitney in a production engine was in 1969, to power the SR-71 Blackbird supersonic reconnaissance aircraft. Commercial jet engine use of these airfoils followed, starting in 1974. This success set the stage for the invention of single-crystal turbine airfoils, and with it much greater efficiency improvements.

### Running the Pigtail

While casting directionally solidified crystals in the late 1960s, AMRDL researcher Barry Pearcey found that if a right-angle bend occurred in the casting mold, a short distance above the knurled chill plate surface (called the "starter" chamber), the number of columnar crystals exiting the bend would be reduced. Two such bends reduced the number even more. Later, while investigating the



properties of single-crystal springs, Giamei found that a helical channel with smooth continuous turning was a natural substructure filter, admitting columnar crystals from the starter and emitting one single crystal to start the single-crystal structure of the turbine blade.

This single-crystal selector was dubbed the “pigtail”; mastering it proved challenging, however. As the single-crystal structure forms, one-dimensional heat conduction must be maintained as the mold is withdrawn from the temperature-controlled enclosure. Any heat conducted to the mold’s lateral surfaces can cause localized crystallization, which disrupts the single-crystal structure with secondary grains.

Pratt & Whitney then refined techniques to manufacture single-crystal turbine airfoils and overcome casting defects such as secondary grains or recrystallized regions. This early pioneering work has been carried on by other manufacturers and improved on over

**A jet engine operates by first taking air in and compressing it. Fuel is added and combusted to heat the air, which then turns the rotor blades of a turbine. The hot exhaust is expelled through a nozzle to create thrust.**

the past 40 years. Yields greater than 95 percent are now commonly achieved in the casting of single-crystal turbine airfoils for aviation gas turbines, which minimizes the higher cost of single-crystal casting compared to conventionally cast blades.

According to Gell, the first single-crystal castings were made from existing polycrystalline alloys. These alloys all contained carbon, boron, and zirconium, three elements that preferentially segregate themselves to grain boundaries, which provides high temperature grain boundary strength and ductility for creep resistance. But in the single-crystal castings, which have longer solidification times and no grain boundaries, these three elements produced compounds with carbons, resulting in poor high and low fatigue properties. In the early 1970s, alloys specifically for single crystals were developed that eliminated carbon, boron, and zirconium, resulting in higher melting points, higher creep strength, and greatly improved high and low cycle fatigue resistance in the final blades and vanes.

An alloy dubbed PWA 1484, which Pratt & Whitney developed in the early 1980s, consists (by weight) of nickel (59 percent), cobalt (10 percent), tantalum (9 percent), aluminum (6 percent), tungsten (6 percent), and a few other elements (10 percent). One of the others is rhenium (3 percent), which provides a significantly higher metal temperature capability. Gell notes that rhenium is a “by-product of a by-product,” derived from specific copper-molybdenum ores, and a very costly element in limited supply. Before committing to the use of PWA 1484, Pratt & Whitney manage-

ment had to be assured that rhenium could be obtained over time at a known, acceptable price. The novel solution was that the company entered into a long-term contract with a Chilean mining company to provide the material.

The first real engine tests of single-crystal turbine blades were carried out in 1967 and 1968 at test facilities in Florida, on the SR-71 Blackbird engine. However, the tests on this supersonic power plant showed that the technology was not ready. Later, in the 1970s, with more mature technology, single-crystal turbine airfoils were installed in P&W F100 production engines, to power the F-15 and F-16 jet fighters. The first commercial aviation use was in the JT9D-7R4 jet engine, which received flight certification in 1982, powering the Boeing 767 and Airbus A310. In 1986, Pratt & Whitney received the ASM International Engineering Materials Achievement Award for the development of single-crystal turbine blades.

Technology history shows that a game changer such as single-crystal turbine blades usually entails a long-term process, typically 30 years or more. Pratt’s AMRDL group did it in less than 10 years, from concept to a marketed product. This targeted group success is worthy of study in itself, something that has been undertaken by Samant Chandrashekar and his colleagues at the National Institute of Advanced Studies in Bangalore, India. The story of the creation of these gems of gas turbine efficiency is an exemplar for others to follow.

Rolls-Royce, one of Pratt & Whitney’s competitors, considers such turbine blades one of their very high-



A mathematical modeling image illustrates how a helical formation selects out a single crystal from a solidifying metal alloy. Each color represents a different crystal grain. (Image courtesy of Charles-André Gandin, CNRS.)



value-added manufacturing core competencies. Computer programs can use a type of mathematical modeling called *finite element analysis* to further refine the single-crystal solidification process.

In jet engine use, single-crystal turbine airfoils have proven to have as much as nine times more relative life in terms of creep strength and thermal fatigue resistance, and over three times more relative life for corrosion resistance, when compared to small-grained crystal counterparts. Modern high-temperature turbine jet engines with long life (that is, on the order of 25,000 hours of operation between overhauls) would not be possible without the use of single-crystal turbine airfoils. By eliminating grain boundaries, single-crystal airfoils have longer thermal and fatigue life, are more corrosion resistant, can be cast with thinner walls—meaning less material and less weight—and have a higher melting point temperature. These improvements all contribute to higher gas turbine thermal efficiencies.

### Engines on the Ground

The newest chapter of the single-crystal story concerns their introduction in large gas turbines used in electric power plants. These units—producing as much as 500 megawatts of electricity, enough to power several hundred thousand homes—are using supersized single-crystal blades and vanes for both corrosion resistance and increased temperature capability, which add to efficiency.

Their first use was for corrosion resistance in a 163-megawatt electric power gas turbine produced by Siemens, introduced to the market in 1995. In more recent years, to increase thermal efficiency, electric power gas turbines inlet turbine temperatures have been increased to aviation levels, and so single-crystal airfoils with higher temperature capacity are now needed for long life.

General Electric's 9H turbine, a 50-hertz combined-cycle gas turbine (meaning it uses its waste heat to produce additional power in a steam cycle), is one of the world's largest. The first model went into service in 2003 at Baglan Bay on the south coast of Wales, feeding as much as 530 megawatts of electricity into the United Kingdom's electric grid at a combined-cycle thermal efficiency of just under



A worker prepares to remove a glowing-hot mold from a furnace after casting. (Image courtesy of Alcoa Howmet.)

60 percent. The 9H, weighing 367,900 kilograms, uses single-crystal turbine vanes and blades with lengths of about 30 to 45 centimeters (the blade lengths in Pratt & Whitney's aircraft engines are about 8 centimeters). Each finished casting weighs about 15 kilograms, and each is a single-crystal airfoil.

Recently, to bring myself up to date on single-crystal casting technology, I visited a foundry where the latest, very large combined-cycle blades are cast. Located in Hampton, Virginia, Alcoa Howmet is a foundry where gas turbine manufacturers such as General Electric, Siemens, Alstom, and Mitsubishi contract turbine blade casting. They can choose directional solidification (expensive), single-crystal (more expensive), or single-crystal with exact lattice orientation specified (most expensive). Because single-crystal properties such as elastic modulus (the tendency of the material to deform along a specific axis) vary with lattice angular orientation, the optimization of this property can improve specific problem areas of blade design, such as creep life or critical vibration modes.

Howmet's vacuum furnaces for casting single-crystal blades are huge. Each is about two stories high, with a lower chamber where the investment casting ceramic mold (which can have multiple cavities to cast a number of blades at once) is positioned for preheating. Then the mold is raised to an upper chamber where pouring of the molten superalloys occurs, under single-crystal conditions. The mold is then lowered at a controlled rate into

the lower vacuum furnace chamber to yield single-crystal solidification. The glowing mold is then cooled and broken apart, freeing the blades to be cleaned and treated for final inspection. All in all, my visit to Howmet showed how much single-crystal technology has advanced since its invention.

As more manufacturers start casting single-crystal blades for such expanded use in power generating turbines, the technology is likely to become less expensive, which means that more widespread power plants may start to use these durable blades. With recent decreases in the price of natural gas, the use of gas in power generation is likely to increase, leading to a more urgent need for reduction in greenhouse gas emis-

sions. The long life of single-crystal blades can help these plants work at higher temperatures and thus maintain efficiency, consequently reducing emissions, for the long haul.

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